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CURRENT SIMULATION METHODS IN MILITARY SYSTEMS VULNERABILITY ASSESSMENT

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Due chiefly to the requirements and opportunities of Live-Fire Testing during the past five years, substantial efforts have been expended by the Ballistic Research Laboratory (BRL) to improve the state of armored-vehicle vulnerability modeling. In order to mirror field observables, the existing point-burst methodology was extended to include the principal sources of stochasticism intrinsic to physical damage processes. This has led to the ability to predict the probability of specific damage states occurring on a shot-by-shot basis. Such damage characterization, when calibrated with Live-Fire experiments, represents for the first time an analytical tool that approaches a "first principles" vulnerability model.

What emerges now is a hierarchy of vulnerability models. At the low end are codes capable of estimating warhead perforation (including residuals) into armored vehicle ballistic hulls and turrets. At the next level is the so-called Compartment-Code methodology. With this level of modeling, all LoFs are related to main-penetrator residuals by lumped-parameter relations. At the high end exist the aforementioned stochastic methods. We further propose that this generic strategy be tailored to all classes of threat/target interactions.

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CURRENT SIMULATION METHODS IN MILITARY SYSTEMS VULNERABILITY ASSESSMENT

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ABSTRACT

Due chiefly to the requirements and opportunities of Live-Fire Testing during the past five years, substantial efforts have been expended by the Ballistic Research Laboratory (BRL) to improve the state of armored-vehicle vulnerability modeling. In order to mirror field observables, the existing point-burst methodology was extended to include the principal sources of stochasticism intrinsic to physical damage processes. This has led to the ability to predict the probability of specific damage states occurring on a shot-by-shot basis. Such damage characterization, when calibrated with Live-Fire experiments, represents for the first time an analytical tool that approaches a "first principles" vulnerability model.

Since the development and application of the stochastic point-burst model, called SQuASH, in the Abrams Live-Fire program, further modifications have been implemented. These include:

- Batch mode capability for thousands of hit points
- Support of more robust Degraded States vulnerability metrics in addition to the traditional Loss-of-Function (LoF) values
- Estimation of spare parts requirements and vehicle repair times
- Calculation of lumped-parameter vulnerability relationships for use in the Compartment Model
- Enhancements to provide stochastic simulation of fragmenting munitions

What emerges now is a hierarchy of vulnerability models. At the low end are codes capable of estimating warhead perforation (including residuals) into armored vehicle ballistic hulls and turrets. At the next level is the so-called Compartment-Code methodology. With this level of modeling, all LoFs are related to main-penetrator residuals by lumped-parameter relations. At the high end exist the aforementioned stochastic methods. We further propose that this generic strategy be tailored to all classes of threat/target interactions.

In this paper the various levels of military-systems modeling will be described together with some candidate techniques now available for utilizing the high-resolution models to calibrate the lower-level vulnerability codes.

1. INTRODUCTION

Historians generally credit Gabriel Mouton, the vicar of St. Paul's Church in Lyon, France, with conceptualizing in 1670 the comprehensive system of weights and measures which was to become the metric system. His notion was to utilize units of measure from the physical universe rather the human body and incorporate a decimal system. Implementation of Mouton's ideas languished for more than a century until the French Revolution of 1789 provided the catalyst for change. A committee of the French Academy of Science recommended in 1791 that the basic unit of length be derived from a measurement of the earth and be equal to 10^{-7} of the distance from the North Pole to the equator. This new "standard" was to become the *metre*. Following a half-decade of effort to resolve a number of technical and political problems involved in the geodesic survey, a formal "prototype metre" was fabricated in 1798 and presented for adoption.

At the outset, the metre was defined in practice by the length of a platinum bar conserved in Paris. About the same time, fifteen iron copies of the prototype were fabricated; one of these copies made its way to the United States and became the standard of measure in this country, serving until 1890. Today the metre is defined not in terms of a mechanical reference but as a multiple of the orange-red line of the spectrum of krypton-86.

We make two observations with respect to standards. First, at any given time the best extant technology provides the *reference* standard— the highest level of accuracy. In the case of the metre, the reference is an *absolute* standard *by definition*. As technology evolves, the reference standard may be redefined to exploit the increased precision of a new technology or device. Second, at any given time *derivative* standards may be fabricated whose accuracy is traceable to a higher level. The highest-level standards, sometimes called *national reference standards*, are often kept under close supervision and ideal environments; their mass utilization is often not practical due to factors of ruggedness, durability or operational overhead. What emerges is a set of *hierarchical* standards, each appropriate for particular applications, with traceability to the top-level reference.

By analogy, substantial efforts today are being focused by the Ballistic Research Laboratory (BRL) on a new generation of precision simulation models. The best of these will constitute *reference standard models* calibrated, to the maximum extent possible, to full-scale field trials. However, unlike the reference standard of length, these reference models will not form absolute standards but rather reflect confidence bounds for accuracy and/or precision traceable by statistical considerations to various measurements. These models will be exercised when their level of accuracy or precision is required; they will also be used to calibrate lower-level codes when greater output detail is not appropriate or possibly when detailed input specification is lacking.

The first vulnerability model developed to support Armored Fighting Vehicles (AFVs) was formulated in 1958.[1] Called the Compartment Code, it was experimentally grounded in full-scale tests performed in the US between 1950 and 1954. It was substantially revised based on some 400 anti-tank firings against M47 and M48 tanks in tests performed in Canada in 1959. Called the CARDE Trials,[2] they established the experimental foundation for essentially the only direct-fire vulnerability model and, by definition, the reference vulnerability code, for the time, as well. The Compartment Model is a relatively unrefined vulnerability code.[3] The target is geometrically modeled in relatively low detail.

1. For a historical perspective on vulnerability testing and modeling, see Paul H. Deitz and Aivars Ozolins, *Computer Simulations of the Abrams Live-Fire Field Testing*, **Proceedings of the XXVII Annual Meeting of the Army Operations Research Symposium**, 12-13 October 1988, Ft. Lee, VA; also **Ballistic Research Laboratory Memorandum Report BRL-MR-3755**, May 1989.

2. *Tripartite Anti-Tank Trials and Lethality Evaluation, Part I*, **Canadian Armament Research and Development Establishment**, November 1959.

3. Bradshaw F. Armendt, Jr., *Methods of Assessing Anti-Armor Weapons Lethality*, **Working Paper 51 of Subpanel 3 of NATO AC/225**, July 1974.

Of the many hundreds of interior components which exist in an actual AFV, only a dozen or so are explicitly analyzed in this model.[‡] Until the past few years, the Compartment Model still served as the reference model for mo. .ssessments of direct-fire weapons against AFVs. A number of more refined codes could in principle have displaced the Compartment Model beginning as long as fifteen years ago.

That more refined codes were not developed until recently is due to a series of required resources that only in the past five years have come in to play. Beyond detailed knowledge of warhead/armor interactions, advanced vulnerability computations require support from a diverse set of disciplines. They include:

- **Behind-Armor Debris (BAD) and Component $P_{K/H}$ Methods and Databases:** High-resolution vulnerability codes explicitly estimate all lethal mechanisms and their potential for killing critical components. Only during the past decade have 1] the analytical methods been developed,[4] 2] the computer-assisted scanning and data-reduction techniques been put in place,[5,6] and 3] a significant number of warhead/armor pairings been examined[7] to enable BAD-based methods to be exploited reliably. Similar progress is also advancing knowledge of component-kill susceptibility.[8]
- **BRL-CAD:** As noted above, vulnerability codes are extremely input intensive. Even baseline codes require the explicit representation of three-dimensional solid geometry. The BRL has established a powerful set of tools called BRL-CAD[9-12] which provide support for the generation, viewing, manipulation and utilization of massive 3-D geometric data bases. Until a few years ago, target descriptions were rarely composed of more than 1500 elements or components. Today some high-resolution descriptions exceed 6000 elements with corresponding ASCII-file sizes in excess of 20 Megabytes. BRL-CAD is now the standard for geometric/material input to vulnerability analyses in the Army and Air Force.

‡ In the Compartment Model only the turret and hull armors, fuel tanks, gun tube, live ammunition and suspension systems are modeled in relatively complete detail.

4. Robert Shnidman, *Direct Fragment Lethality Inference from Witness Plate Array Data*, **Proceedings of the ADPA Tenth Annual Symposium on Survivability and Vulnerability (SECRET-NOFORN)**, 10-12 May 1988, San Diego, CA.

5. Robert Shnidman, *HOLES Program Documentation*, **BRL Software**, July 1988. (Unpublished)

6. Gary S. Moss, *FRED Program Documentation*, **BRL Software**, February 1989. (Unpublished)

7. D. L. Rigotti, P. H. Deitz, D. F. Haskell, M. W. Starks, D. P. Kirk, O. T. Johnson, J. R. Jacobson, W. Kokinakis, J. T. Klopcic and G. A. Bowers, *Vulnerability/ Lethality Assessment Capabilities- Status, Needs, Remedies*, **Ballistic Research Laboratory Special Publication BRL-SP-74**, December 1988.

8. Robert Shnidman and Todd J. Fisher, *Abrams Tank System Component Vulnerability- Test Procedures and Results*, **Ballistic Research Laboratory Memorandum Report**, In Preparation.

9. M. J. Muuss, P. C. Dykstra, K. A. Applin, G. S. Moss, P. R. Stay and C. M. Kennedy, *A Solid Modeling System and Ray-Tracing Benchmark Distribution Package*, **Ballistic Research Laboratory CAD Package, Release 3.0, SECAD/VLD Computing Consortium**, 2 October 1988.

10. Paul H. Deitz, William H. Mermagen, Jr., and Paul R. Stay, *An Integrated Environment for Army, Navy and Air Force Target Description Support*, **Proceedings of the ADPA Tenth Annual Symposium on Survivability and Vulnerability**, 10-12 May 1988, San Diego, CA; also **Ballistic Research Laboratory Memorandum Report BRL-MR-3754**, May 1989.

11. Michael J. Muuss, *Understanding the Preparation and Analysis of Solid Models*, in **Techniques for Computer Graphics**, ed. Rogers and Earnshaw, Springer-Verlag, 1987.

12. Paul H. Deitz, Michael J. Muuss and Edwin O. Davisson, *Issues in Automatic Object Recognition: Linking Geometry/Material Data to Predictive Signature Codes*, **In the First Proceedings of the Society of Photooptical Instrumentation Engineers (SPIE) Advanced Institute Program on Automatic Object Recognition**, 21-23 April 1990, Coco Beach, FL; also **Ballistic Research Laboratory Memorandum Report**, In Press.

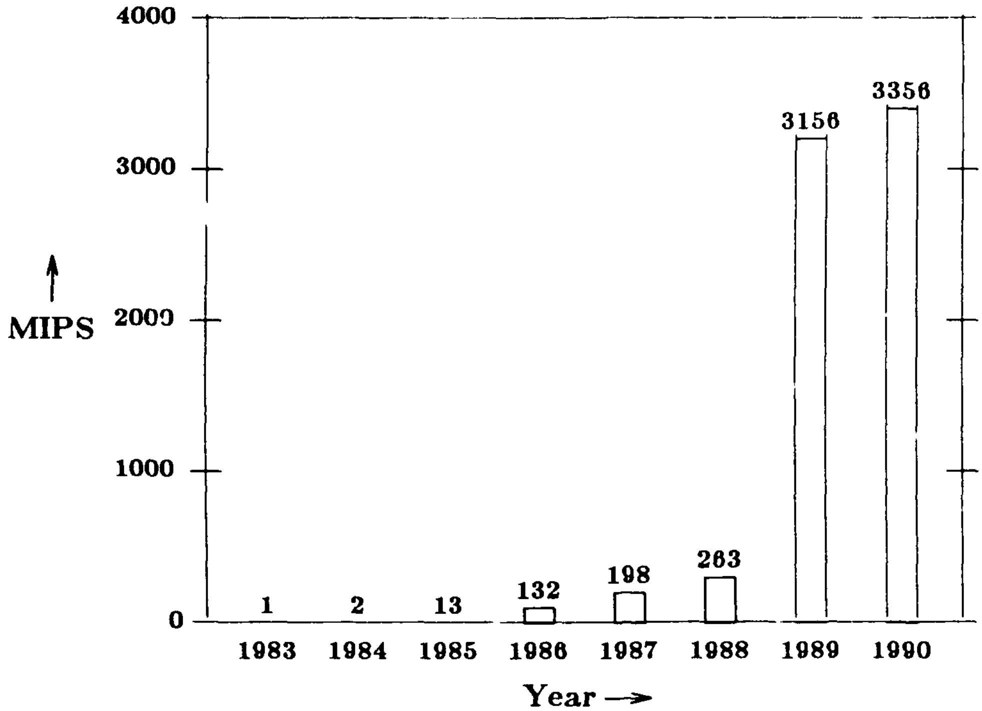

Figure 1. Plot of VLD Computing Capability *versus* Year for the past eight years. A single unit of performance is based on benchmarks established with the BRL-CAD package ray interrogation library and is equivalent to approximately one million instructions per second (MIPS), about the speed of a DEC VAX 11/780.™

- **Extensive Computer Hardware:** Modern computer codes require large amounts of computer power to 1] generate the copious volumes of input data, supported by interactive graphics, 2] process many millions of computations during batch-code execution, and 3] assist in the sorting, displaying and interpreting the code results, increasingly with advanced statistical packages. Figure 1 shows the growth in computing power in the Vulnerability Lethality Division (**VLD**) for the past eight years.
- **Uniform UNIX™ Operating System Environment:** The ability to compile and execute monolithic FORTRAN code modules is no longer adequate to support modern analytic methods. The development and execution of modern software requires powerful editors, compilers, system subroutine libraries and high-resolution graphical display devices; also uniform intra- and intermachine communication methods for the rapid passing of data at various stages of processing. Essentially all VLD computing machines run UNIX.
- **Live-Fire Test Programs:** The National Defense Authorization Act for FY 1987[13] required that all major weapon systems undergo live-fire testing (**LFT**) prior to entering full-scale production. This program, with the requirements for detailed preshot predictions and the opportunity for detailed post-shot examination of over-matched, fully configured AFVs, has been most significant.

13. *Live Fire Testing*, **National Defense Authorization Act for FY 1987**, contained in Chapter 139, Section 2366 of Title 10, United States Code.

As the program has proceeded it has highlighted much-needed extensions in experimental data bases, inadequacies of extant modeling methods and required statistical methodology. As various AFVs have been tested, not only full-scale test results have accrued, but also many critical supporting data bases dealing with penetration, BAD and component $P_{K/H}$'s have been established. Various LF programs have frequently funded critical methodology extensions when alternate resources were unavailable.

- **SQuASH (*S*tochastic *Qu*antitative *A*ssessment of *S*ystem *H*ierarchies):** In response to the benefits and burdens of LFT, this advanced stocnastic vulnerability code (to be reviewed below) was established.[1,14] From this new and rapidly evolving computation tool, a new reference methodology is being established which can serve as a new vulnerability standard for a diverse set of V/L requirements.

This paper targets a number of objectives. We begin by reviewing the uses and applications of various types of Vulnerability/Lethality (**V/L**) data. We will note various aspects of V/L practice which have been the focus of both external and internal criticism. Next, a framework within which V/L modeling can be understoo will be presented and illustrated with various aspects of both testing and modeling practices. Following this, the full utility of the SQuASH vulnerability model will be described with its applications to various required tasks. We will describe a strategy for validating SQuASH *via* tests of diverse military targets (with relevant threats) to form a reference model set capable of supporting both high-demand predictions as well as supporting a hierarchy of lower-resolution models. Finally, we will discuss future directions for V/L modeling.

2. USES OF V/L MODELS

The potential uses of V/L models are many and varied. For completeness, we review some of the principal applications:

- **Major Milestone Decisions:** All major Army systems must pass a series of milestone decision points. The studies which drive these decisions require vulnerability data, historically in terms of Catastrophic (**K**) Kill and Mobility (**M**) and Firepower (**F**) Loss-of-Function (**LoF**) estimates.

- **Concept Tradeoffs:** Within the development process there frequently is a need to downselect concepts, technologies, or contractors. V/L assessments provide key inputs for these studies.

- **Data for Decision Makers:** Apart from major decision milestones, Army leadership commissions numerous *ad hoc* studies to help with in-process reviews (**IPRs**), Program Objective Memorandum (**POM**) submissions, reprogramming actions, Congressional inquiries an ' resource decrement drills. V/L estimates are a critical input for these studies, second in importance only to cost.

- **Inputs to War Games:** War game outputs such as loss-exchange-ratios are an important data point throughout the Acquisition Process; they are also critical in helping **TRADOC** (USA **T**raining **and Doc**trine Command) in its continual reformulation of warfighting doctrine, tactics and **O**perational and **O**rganizational (**O&O**) Plans. Perhaps the most dominant variable in a typical force-level simulation or wargame is the V/L estimate.

- **Vulnerability Reduction:** Protection for AFVs from an array of modern threats is a key consideration both for fielded systems as the threat changes and grows and also for vehicles throughout the development cycle. During the concept stages, generally only the armor package,

14. A. Ozolins, *Stochastic High-Resolution Vulnerability Simulation for Live-Fire Programs*, **The Proceedings of the Tenth Annual Symposium on Survivability and Vulnerability of the American Defense Preparedness Association**, Naval Ocean Systems Center, San Diego, CA, 10-12 May 1988.

fuel and ammunition stowage are amenable to analyses. As system detail grows, interior component placement and vulnerability susceptibility and system redundancies become issues.

- **Lethality Optimization:** The acquisition of a system to deliver a warhead must be based on its ability to disable specific targets. Often many design tradeoffs must be weighed in order to achieve an optimum design. V/L codes provide key guidance in this objective.

- **SPARC (*S*ustainability *P*redictions for *A*rmy Component *R*equirements for *C*ombat:** For many years the Army stockpiled spare parts for ground vehicles based on peacetime failure rates, despite the fact that there was little reason to suspect that such a stockpile would be optimally useful for repairing combat-damaged vehicles. With the help of component-level V/L predictions, the logistics community is now better equipped to develop appropriate stockpile needs.

- **Planning and Analysis of LF Testing:** Although earlier a point of contention,[15] it is now widely acknowledged that LF testing alone cannot provide a complete vulnerability picture of a vehicle. High-resolution modeling methods are indispensable for delineating test configurations for which high- or low-predictive capability may exist.[16,17] They are also indispensable for "bootstrapping" valuable, but contextually limited, full-up and off-line experimental data into a more complete picture of overall vehicle vulnerabilities.

- **Use cf Reference V/L Models for Calibration:** As implied above and will be illustrated below, V/L models reflecting a given level of accuracy can be used to calibrate lower-resolution models which for certain applications may have advantages of speed or input preparation or for when detailed input information may not be available.

- **Generation of New Measures-of-Effectiveness (MoEs):** In many instances, the desired output of a V/L model is not a characterization of system damage *per se* but rather a related figure-of-merit or MoE. The standard metrics for AFV studies are the K-Kill and M and F LoFs mentioned above. As new systems are conceived and new strategies evolve, users of V/L data sometimes require higher resolution figures-of-merit than the traditional M and F LoFs. When new systems are developed for new battlefield roles, sometimes new MoEs must be defined. High-resolution V/L models capable of capturing detailed system design and damage characterization are critical to def ning improved figures-of-merit.

3. CRITICISM OF V/L PRACTICE

The various uses of V/L data which were detailed in the previous section demonstrate the critical importance of VLD's work in the research, development and acquisition process. When the importance of the work is considered in light of the relatively unrefined simulation tools which have traditionally been used for the calculations, it is easy to understand why the V/L assessment process has been a magnet for high-level attention and criticism. Over the past thirteen years the VLD has been reviewed by more than a dozen oversight committees. It has periodically conducted its own self examinations. A sampling of these events includes:

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15. *Live Fire Testing: Report to the Chairman, Subcommittee on Seapower and Strategic and Critical Materials, Committee on Armed Services, House of Representatives,* **United States General Accounting Office Report GAO/PEMD-87-17,** August 1987, p. 124.

16. C. J. Dively, S. L. Henry, J. H. Suckling, J. H. Smith, W. E. Baker, D. W. Webb and P. H. Deitz, *Abrams Live Fire Test Program: Comparison Between SQuASH Predictions and Field Outcomes (U),* **Ballistic Research Laboratory Special Report (SECRET),** February 1989.

17. Paul H. Deitz, Jill H. Smith and John H. Suckling, *Comparisons of Field Tests with Simulations: Abrams Program Lessons Learned,* **Proceedings of the XXVIII Annual Meeting of the Army Operations Research Symposium, 11-12** October 1989, Ft. Lee, VA, pp. 108-128; also **Ballistic Research Laboratory Memorandum Report BRL-MR-3814,** March 1990.

- 1977: The Hardison Report on the Review of the Vulnerability Program
- 1977: Plans for Updating the Armored Vehicle Lethality/Vulnerability Methodology and Data Base[18]
- 1978: Letter— GEN Starry to GEN Guthrie on Problems that Plague the Analytical Community
- 1978: Letter— GEN Guthrie to GEN Starry on Resource Requirements for Vulnerability and Performance Data
- 1982: Memorandum for Record on Air Defense Evaluation— Mr. Walter Hollis
- 1985: Defense Science Board Report on Armor Anti-Armor Competition
- 1986: USA Laboratory Command (LABCOM)-Sponsored Los Alamos Review on Live-Fire Testing and Methodology
- 1986: Department of the Army Inspector General Review of the Bradley Fighting Vehicle/Joint-Live Fire Programs
- 1986: Board on Army Science and Technology (BAST) Report on Shot Selection Process for Live-Fire Testing
- 1987: USAMARDA Manpower Survey of the Vulnerability/Lethality Division
- 1987: US Army Audit Agency- Materiel Survivability and Vulnerability
- 1987: Peer Review Group (R. Andreas, J. W. Tukey and M. Wilkins)
- 1987: General Accounting Office (GAO) Live-Fire Testing Report[15]
- 1987: Vulnerability/Lethality Assessment Capabilities- Status, Needs, Remedies[19]
- 1989: Board on Army Science and Technology Report on Vulnerability Assessment Methods [20]
- 1990: Vulnerability Methodology Review, Convened by the Director, Ballistic Research Laboratory
- 1990: Letter— Mr. Abraham Golub to Mr. Walter Hollis, Review of the Board on Army Science and Technology (BAST) Review of the Army Assessment Methodology Concerning Vehicle Vulnerability to Anti-Armor Weapons
- 1990: JASON Review of the Army Approach to Vulnerability Testing

Many of the suggestions and recommendations made by these committees concern matters which are not directly relevant to the methodological issues discussed in this paper. Such matters include:

- The Army's institutional failure to implement recommendations of previous studies.
- Organizational bias/independent assessment issues.

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18. D. F. Menne, G. L. Durfee, R. L. Kirby, J. P. Lambert, M. L. Lampson, J. J. Ploskonka, J. R. Rapp and E. P. Weaver, *Plans for Updating the Armored Vehicle Lethality/Vulnerability Methodology and Data Base*, **Special Report for the Director, Ballistic Research Laboratory**, 22 August 1977.

19. D. L. Rigotti, P. H. Deitz, D. F. Haskell, M. W. Starks, D. P. Kirk, O. T. Johnson, J. R. Jacobson, W. Kokinakis, J. T. Klopcic and G. A. Bowers, *Vulnerability/Lethality Assessment Capabilities- Status, Needs, Remedies*, **Ballistic Research Laboratory Special Publication BRL-SP-74**, December 1988.

20. *Armored Combat Vehicle Vulnerability to Anti-armor Weapons: A Review of the Army's Assessment Methodology*, Committee on a Review of Army Vulnerability Assessment Methods, Board on Army Science and Technology, **Commission on Engineering and Technical Systems, National Research Council**, National Academy Press, Washington, D.C., 1989.

- Insufficient funding/staffing issues.
- Lack of appropriate input data for V/L models.

However, also of interest is the fact that deficiencies in the existing suite of V/L models were noted by many of the groups. Three prominent examples are the BAST review, the LABCOM-sponsored Los Alamos Review and the Golub Review. In the 1986 Report on Vulnerability Assessments, the BAST concluded that models in their current state leave much to be desired. In the 1986 Los Alamos Review, equally strong conclusions were drawn about V/L modeling:

- Characterize models in terms of variability of their output relative to their input.
- Modeling effort at BRL could be increased several fold and the cost would still be insignificant compared to overall cost of the program.

Finally, the 1990 Golub Review explicitly suggested that SQuASH be made the primary member of a vulnerability modeling hierarchy. The modeling strategy in this paper is intended to be responsive to these suggestions.

4. V/L FRAMEWORK

In an earlier paper[1] we introduced the notion of "**Spaces**" of vulnerability. That notion is reiterated here because it provides an extremely useful framework into which the many test/model configurations, processes/transformations and intermediate/final observations can be clearly and concisely cast.

Figure 2 is meant to represent four **Spaces** of vulnerability. **Space 1**] describes all possible encounters of a particular threat with a given target. Each point within the space represents a single configuration prescribing the attack of the target by a warhead. It is appropriate to think of a point within **Space 1**] as representing the complete pre-shot physical characterization of a live-fire test including the warhead, the target and the warhead attitude and hit-point with respect to the target. **Space 1**] is clearly infinite. Even if the space were restricted to a single warhead, single target and single intended aimpoint, the number of attack configurations is infinite. Further, even with the most detailed information concerning a highly calibrated test, certain information critical to the test outcome cannot be known ***a priori***. Such information includes the ***exact*** physical specification of the warhead, the ***exact*** specification of the armor and vehicle components, the ***exact*** juxtaposition of the warhead and target at the moment of impact (as in the case of the **K**inetic **E**nergy [**KE**] round) or warhead initiation (as in the case of the **C**hemical **E**nergy [**CE**] round).

Space 1], while establishing a complete set of initial (preshot) conditions describing the threat and the target, ***says nothing*** concerning the V/L mechanisms of damage and how they occur. This is the province of the mapping function, symbolically represented as the upper-most arrow in Fig. 2. The arrow can be thought of as an *operator* which transforms a state of **Space 1**] to a state of **Space 2**]. In an entirely equivalent sense a live-fire shot can be thought of as the real-world operator which performs the same transformation. As we'll see later, the SQuASH vulnerability code was configured in such a way as to replicate the same mapping function. Each point in **Space 2**] represents a list of vehicle components which have been killed by the event. Associated with that vector is a list of post-shot observables such as armor entry/exit holes, observed fragment effects, etc. The ***subset*** of **Space 2**] characterizing component-damage vectors is large, but ***not*** infinite, having a maximum size of 2^n, where n is the number of critical components[†] constituting a particular military system. Given the inherent

† A ***critical component*** of a military system is a component which if damaged or destroyed could ***potentially*** lead to a partial or total loss of a mission-supporting function. Such functions include mobility, firepower, communications and the ability to acquire enemy targets.

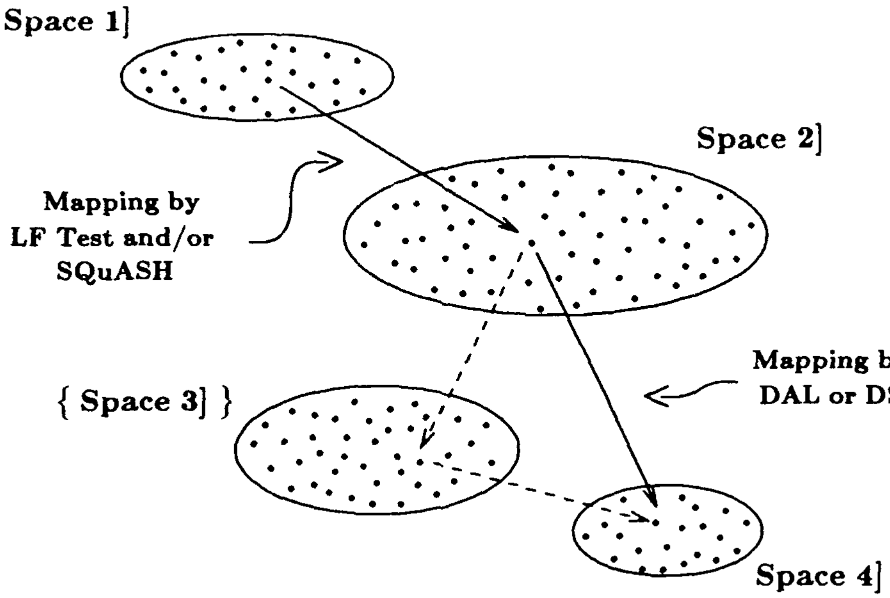

Figure 2. Four Spaces of Vulnerability. Space 1] represents all combinations of specific warhead/target initial conditions. A given point represents one complete set of specifications. Individual points in Space 2] represent particular damage vectors, *i.e.* particular combinations of killed critical components, plus all post-shot damage observables such as armor exit holes, fragment effects, etc. The maximum size of the subset of Space 2] describing damage vectors is 2^n, where n is the number of critical components in the target. Space 3] represents objective Measures-of-Performance and is not modeled so the related mapping processes are indicated as dashed lines. Space 4] characterizes various Measures-of-Effectiveness; the mapping process for ground vehicles has historically been *via* the Damage Assessment List (DAL). In the future all mapping will be *via* the Degraded States (DS) methodology.

variability of the many variables described above, it is likely, even to be expected, that if an experiment were repeated numerous times, many arrows would be observed, all emanating from a single point in **Space 1]**, and mapping to many different points (damage vectors) in **Space 2]**.[§]

Space 3] is the space of Measures-of-Performance (**MoP**). MoPs would typically include objective measures of automotive performance (*e.g.* top speed, acceleration, rough-terrain crossing ability) and firepower (*e.g.* rate-of-fire, time-to-acquire, hit dispersion). Given a specific damage vector (point) in **Space 2]**, the above-mentioned MoPs could ***in principle*** be objectively measured in the field. The relationship between **Space 2]** damage states and **Space 3]** MoPs, though of great potential utility, has never been developed, and, hence, the associated mappings to and from **Space 3]** are shown as dashed lines and the **Space 3]** label is enclosed in curly brackets ({ }).

§ An interesting variant of this case is to consider a sequence of ***different*** experiments performed in **Space 1]**. Given many such experiments in which the warhead/target configuration were varied (*i.e.* sampling different points of **Space 1]**), cases could be observed in which the *same* damage vectors occurred. This would be described by multiple arrows originating at different points in **Space 1]** but terminating at the same point in **Space 2]**.

The last space of vulnerability is **Space 4]**, a space of **Measures-of-Effectiveness (MoE)**. For many years these measures have been known as probabilities of catastrophic kill (probability of K Kill), and **Mobility** and **Firepower Loss-of-Function (M** and **F LoF)**. In the past the mapping from **Space 2]** to **Space 4]** was accomplished by means of the **Damage Assessment List (DAL)**. Described elsewhere,[1] this process is being replaced by an improved mapping process called **Degraded States (DS)**.[21-23]

The issue which lies at the heart of V/L field tests and/or simulations is the statistical characterization of these spaces. For example in the case of **Space 1]**, even if this domain can be artificially limited by reducing the number of threats and interaction geometries with a specific target, the variability of warhead penetration and other phenomenologies introduced by the projection from **Space 1]** to **Space 2]** nevertheless gives **Space 2]**, the physical domain within which all observations take place, a high level of complexity. Stated slightly differently, for a particular warhead/target interaction in **Space 1]**, what is the dimensionality of **Space 2]**, *i.e.* how many individual damage vectors compose the space of the 95th percentile? Such issues were the focus of Ref. 17, and statistical tests were used where possible for all physical observables. As we have also observed, if a model can accurately predict the statistical behavior of a V/L test with respect to the physical observables of **Space 2]**, then the (mapped) metrics of derived spaces (*e.g.* **Space 4]**) must agree.[24] Thus issues of ***accuracy*** and ***precision*** in the context of V/L considerations can only be calculated in **Space 2]**, since model accuracy ***by definition*** implies some statistical convergence with the real world and by our paradigm, the post-shot real world is embodied ***only*** in **Space 2]** metrics.

Finally using these spaces, all V/L models can be described within this framework. The Compartment Model was based on a series of firings[2] in which each shot (defined by a point in **Space 1]**) resulted in a set of killed components (damage vector) and armor exit hole (both of **Space 2]**). For each test the damage vector was mapped from **Space 2]** to **Space 4]** ***in a partly subjective process*** by the following procedure. The DAL was established to relate the ***total*** loss[∞] of any ***single*** major component/system directly to overall vehicle M and F LoF values. Utilizing the DAL for post-shot assessments required taking into account two complications— fractional (partial) system kills and/or multiple-system kills. To handle partial kills, the DAL entries were scaled by fractional kill values based on assessor judgements. To handle multiple-system kills, the scaled system LoFs were combined using a Survivor Rule type of relationship.[§] The total vehicle LoFs (*i.e.* the M and F metrics) were then decomposed into the contributions attributable to particular vehicle regions (*i.e.* compartments).[□] The resulting points were used to generate curves expressing the relationship between armor exit hole[□] and the M and F LoFs for the crew and engine compartments.[‡] During actual execution of the

21. Michael W. Starks, Lisa K. Roach and John M. Abell, *Degraded States Vulnerability Analysis*, **Ballistic Research Laboratory Technical Report BRL-TR-3010**, June 1989.

22. John M. Abell, Bruce A. Rickter and Mark D. Burdeshaw, *Degraded States Vulnerability Methodology - Phase II*, **Proceedings of the XXIX Annual Meeting of the Army Operations Research Symposium**, 10-11 October 1990, Ft. Lee, VA.

23. Gary R. Comstock, *Degraded States Weapon Analysis Research Simulation (DSWARS)*, **Proceedings of the XXIX Annual Meeting of the Army Operations Research Symposium**, 10-11 October 1990, Ft. Lee, VA.

24. Michael W. Starks, *Assessing the Accuracy of Vulnerability Models by Comparison with Vulnerability Experiments*, **Ballistic Research Laboratory Technical Report BRL-TR-3018**, July 1989.

∞ A system Loss-of-Function is *not* Bernoulli in nature but can take values $0.0 \leq \text{LoF} \leq 1.0$.

§ The "*LoF*" *Survivor Rule* states that the overall LoF of an AFV consisting of **n** independent systems, each with its own Damage Assessment Value, D_i, and system Fractional Kill, F_i, is given by:

$$\text{LoF} = 1 - \left[\left(1 - D_1 F_1 \right) \times \left(1 - D_2 F_2 \right) \times \quad \left(1 - D_n F_n \right) \right]$$

□ For shaped-charge threats, the hole diameter was used for the crew compartment and was combined with the residual penetration (*i.e.* residual hole volume) for the engine compartment.

‡ Since the application of the Compartment Model to the M1 vehicle, an ammunition compartment has been added.

Compartment Model, the various Compartment LoFs are aggregated using a variant of the Survivor Rule† given earlier. Thus the Compartment Model uses an extremely incomplete characterization of **Space 2]**, armor exit hole (or residual penetration), to provide mapping relationships to the expected M or F LoFs of **Space 4]**.

Figure 3 gives one of the damage-correlation curves for the Crew Compartment based on the early CARDE tests.[2] Here the Mobility (M) LoF is plotted against the Profile Hole Diameter, a parameter related to the hole diameter on the inner surface of the armor. These data were collected for a series of Chemical Energy warheads ranging in size from 5" to 8"; firings were conducted against both M47 and M48 tanks.

The class of vulnerability models called point-burst codes describe explicitly the behind-armor debris environment and its interaction with the vehicle interior components; it can be understood as the following mapping processes. Codes such as VAST[25] and SLAVE[26] estimate the probability of killing each vehicle interior component for a given shot. In contrast to the manner in which the CARDE data were processed, all of the vehicle major systems are decomposed into their constituent components. The components are cast into fault trees which reflect the series/parallel design of the systems. Then the individual component kills are rolled up using the standard laws of probability for independent series or parallel constructs as reflected in the fault trees. The resulting system LoFs are finally combined using the procedure described above for the CARDE Compartment-Code calibrations. Two related issues are that 1] the probability procedures applied to the (critical) component PKs and 2] the Survivor-Rule procedure applied to system LoF aggregation are strictly applicable only under the assumption that the elements being processed (components and/or systems) are ***independent***, one from another. Based on analyses of tests reported in Ref. 17, we know that component kills are, in fact, statistically ***dependent***. The net result is a ***biased**** estimate of the overall system first-moment values for the M and F LoFs. Expected-value point-burst models have not been typically configured to infer actual **Space 2]** damage vectors but have resorted to the above-described processes to proceed directly to expected-value LoFs.

Finally, SQuASH is a point-burst model into which stochastic processes have been introduced. Through repeated Monte Carlo draws, an attempt is made to demonstrate the possible variability of single live-fire shots. The effect is to repeat the mapping projection from **Space 1]** to **Space 2]** to derive individual outcomes of damage vectors. Bernoulli outcomes (either kill or no-kill) are assigned to all classes of components.□ Thus using SQuASH, we have attempted for the first time to model the full characterization of damage vectors in **Space 2]**. The key metrics of **Space 2]** can then be used to compare with field tests§ as well as to map unambiguously to **Space 4]** for the required MoEs. In SQuASH the fault-trees are assembled in identical fashion as required in the expected-value point-burst codes. However, since all components are either killed or not-killed, system functions are either fully supported (*i.e.* there is at least one unbroken path through the fault tree) or completely unsupported

† The version of the *Survivor Rule* used in the Compartment-Model calculations states that the overall LoF of an AFV consisting of **n** independent compartments/major systems, each with its own LoF_i is given by:

$$\mathrm{LoF} = 1 - \Big[[1 - \mathrm{LoF}_1] \times [1 - \mathrm{LoF}_2] \times \quad [1 - \mathrm{LoF}_n] \Big]$$

25. C. L. Nail, *Vulnerability Analysis for Surface Targets (VAST)- An Internal Point-Burst Vulnerability Assessment Model - Revision I*, **Computer Sciences Corporation Technical Manual** CSC **TR-82-5740**, August 1982.

26. D. A. Ringers and F. T. Brown, *SLAVE (Simple Lethality and Vulnerability Estimator) Analyst's Guide*, **Ballistic Research Laboratory Technical Report ARBRL-TR-02333**, June 1981, AD B059679.

* The amount of this bias is unknown at this time.

□ The rationale for this binning process is discussed in Ref. 17.

§ An issue here is the reliability and consistency with which field assessors can bin *partially* killed (*i.e.*damaged) components to crisp kill/no-kill states.

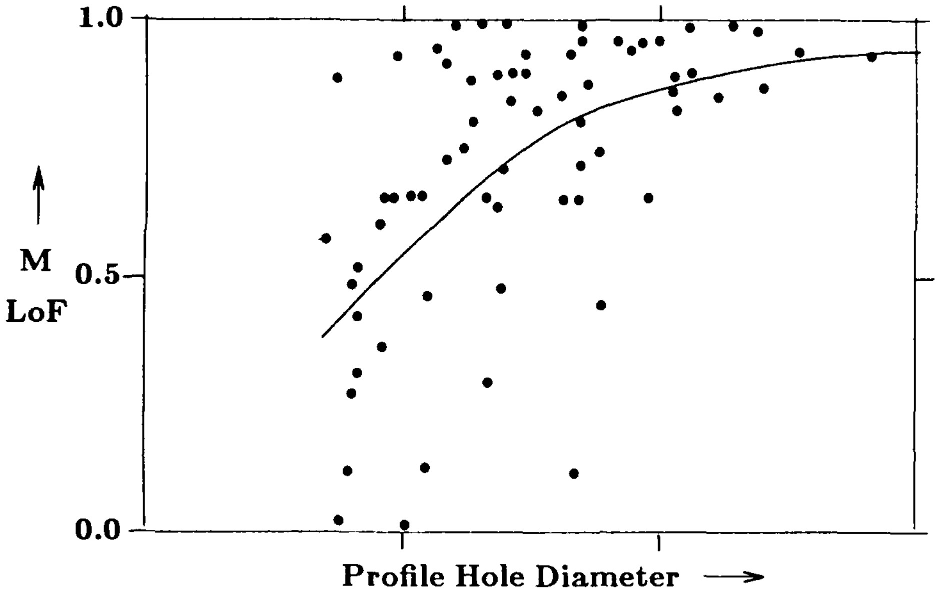

Figure 3. Mobility LoF vs. Profile (≃ Exit) Hole Diameter. Data (*circa* 1959) from CARDE Tests[2] for a series of Chemical Energy (CE) warheads ranging from 5" - 8".

(*i.e.* there is no unbroken path through the fault tree). At the major component/system-level entry points to the DAL process, multiple system kills are unavoidably combined *via* the Survivor Rule when two or more kills occur. As we will see later, the Degraded States methodology avoids altogether the need for using the Survivor Rule.

The importance of **Space 2**] characterization as the *only* domain within which issues of model accuracy[24,27] can be grounded went unappreciated by the BAST[20] during their 1989 assessment. The first VLD attempt at comparisons[17] merely showed some of the possibilities for statistical analyses. Recent work at Institute for Defense Analyses[28] has provided three new statistical tests for comparing field and predicted damage vectors. Ongoing work by the JASONs[29] is also targeted to developing statistical methods for LF-test/SQuASH-model comparisons in **Space 2**].

We will now review the *reference* model being developed to act as the *standard* for V/L methodology.

5. SQuASH AS KEY MEMBER

For SQuASH to serve as the reference model for Vulnerability/Lethality methodology, it must embody the highest level technical understanding of threat/target interaction available. Furthermore, this technical understanding must be anchored in experiment through validation with full-scale field tests.

27. Michael W. Starks, *Vulnerability Science: A Response to a Criticism of the Ballistic Research Laboratory's Vulnerability Modeling Strategy*, Ballistic Research Laboratory Technical Report BRL-TR-3113, June 1990.

28. L. Tonnessen, A. Fries, L. Starkey and A. Stein, *Live Fire Testing in the Evaluation of the Vulnerability of Armored Vehicles and Other Exposed Land-Based Systems (U)*, Institute for Defense Analyses Paper P-2205 (SECRET), July 1989.

29. Private communication with Oscar Rothaus, member, JASON Committee to Investigate Vulnerability Testing, La Jolla, CA, July 1990.

In the previous section, some of the technical differences among the various V/L codes were detailed. In this section we will enumerate the technology advances of SQuASH beyond previous models, detail the plan for validating the model, and give some recent extensions of SQuASH that, when taken together, will establish SQuASH as the reference model.

5.1 Technical Improvements Provided by SQuASH

5.1.1 Stochasticism: The most significant improvement to SQuASH over previous models is the inclusion of random sampling for the variables that contribute to the vehicle LoF. All previous models computed only an expected-value estimate of the vehicle LoF, with no associated variability of the estimate. With the need to compare the predicted outcome of a given shot from live-fire tests with an actual observed outcome, the addition of the random nature of the phenomena is critical in making statistically valid and meaningful comparisons. Furthermore, there are no statistically valid decision criteria based only on expected-value point estimates of random variables.

5.1.2 Physics for Kinetic Energy (KE) Penetrators: SQuASH makes two improvements over earlier models to represent more accurately the threat/target interaction under some specific conditions. First, SQuASH allows KE penetrators to deflect through the target geometry rather than traveling only along a straight path and, second, it allows KE penetrators to fracture, with the separate pieces tracked through the target where this phenomenon is expected.

5.1.3 Truncation of Intermediate Results: Many of the older V/L models truncate calculation along a shotline when the accrued damage to the vehicle reaches unity. This is done to reduce the computation time and storage required to run the code. In contrast, SQuASH saves all intermediate output. If a penetrator perforates the armor and travels through five components, even though the first component may cause complete loss-of-function, all other components and the intermediate damage are stored. This is important for the development of lower-level models where the distribution of hits on given components or other information may be of interest. If this information is truncated, it can also give biased estimates of the vulnerability of individual components.

5.1.4 Improved Realism: An additional advantage of the SQuASH model is the similarity between the structure of the code and the actual physical processes as they occur in the real world. This structure facilitates comparisons between the model and the field data that can be observed at any stage in the process. In particular there is no combining of effects; each is modeled explicitly.

Before SQuASH, as discussed above, no V/L codes provided estimates of actual component-damage vectors for repeated sampling of warhead/target interaction. Also as noted, since these **Space 2**} metrics are the modeling-world equivalent of test observables, without them model calibration is problematic at best, and validation is impossible.

5.2 Recent SQuASH Extensions

Since the original Abrams program LF requirements, the SQuASH environment has been extended to support other classes of V/L computations. They will be reviewed briefly now.

5.2.1 Batch Computation: The original configuration of SQuASH, as previously noted, was targeted to single-shot predictions. Once all the inputs were assembled, the computation proceeded in two stages. The first involved extensive geometric interrogation *via* raycasting to replicate possible warhead/target paths as well as vehicle interior components behind the armor potentially susceptible to residual penetrator and BAD damage. This part of the processing required a substantial amount of processing ($\sim$ 30 minutes of CRAY 2 time for a single shot location).

The second involved the actual vulnerability computations leading to the **Space 2**} damage vectors and LoF histograms. This calculation took substantially less time. Nevertheless, the application of SQuASH to many thousands of hit points from, for example, a single aspect angle was not practical.

Considerable effort was expended to reduce the run-time. A data-compaction scheme was developed to reduce the total number of ray calculations required for the interior component solid angle

calculations. The result is a run overhead for SQuASH that is consistent with previous point-burst models such as VAST[25] and SLAVE.[26]

5.2.2 Support for Degraded States: The initial use for the batch-mode calculational procedure just described was in support of the improved V/L methodology called **D**egraded **S**tates (**DS**). Traditional vulnerability calculations make use of a mapping procedure called **D**amage **A**ssessment **L**ists (**DALs**) or **S**tandard **D**amage **A**ssessment **L**ists (**SDALs**). A DAL maps killed components (**Space 2**]) and sets of components into loss of combat function (LoF) in **Space 4**]. However, the use of DALs in the process of developing vulnerability measures-of-effectiveness is conceptually and mathematically problematic.[30] The Degraded States Vulnerability Methodology,[21] developed by the BRL and the **A**rmy **M**ateriel **S**ystems **A**nalysis **A**ctivity (**AMSAA**) is a material improvement in both the fundamental method by which vulnerability estimates are calculated and in the clarity, objectivity and usefulness of the estimates themselves. The DS methodology overcomes the problems associated with the DAL. It is fully auditable and, therefore, subject to correction and improvement. It is also completely sound from a mathematical point of view. Most important, it provides a much more robust account of vehicle capability as a function of specific damage sustained. This robustness substantially improves the Army's capability to model accurately the effects of damaged, but operational, vehicles on the battlefield.

The tradition has long been to describe vehicle Loss-of-Function in terms of mobility and firepower. For the new approach, a more robust set of metrics was developed. The functions of a tank were divided into six categories: **MOBILITY, FIREPOWER, ACQUISITION, CREW, AMMUNITION** and **COMMUNICATION**. Each category contains a set of kill definitions which describe degraded, but operational, states of the tank. Particular tank subsystems which support each category/kill definition were identified and committed to fault-tree analyses.[31] Damage was then assessed against the various vehicle subsystems used to represent the category/kill definitions for a particular set of threats. The probabilities of the various combinations of kill definitions for each subsystem were calculated based on the SQuASH estimates within each four-inch cell from a particular direction of attack. These estimates were calculated for both the Degraded States vulnerability approach and the DAL approach. The probability distributions were provided to AMSAA for support in demonstrating the new metrics in force-level modeling and have been supplied to many other downstream consumers of V/L products. BRL is in the process of fully implementing this improved approach to **Space 4**] MoEs.

5.2.3 Support for SPARC Calculations: A second important use of the batch-mode version of SQuASH has been to determine appropriate spare-parts stockages for combat-damaged materiel. Although not part of the original code design,[14] the batch-mode capability together with significant algorithm extensions[‡] have provided for SPARC capability with direct-fire weapons. Here it is not the **Space 4**] MoEs that are of interest, but the **Space 2**] damage vectors. Clearly, this class of calculation would not be possible at all without credible component-level modeling at the SQuASH level of detail.

This methodology is currently being extended to indirect-fire (*i.e.* artillery) weapons as well.[‡] For many years the standard vulnerability metric computed for such encounters has been (expected) ***vulnerable area***. However vulnerable area, like the M and F LoFs, cannot be compared with specific

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30. Michael W. Starks, *New Foundations for Tank Vulnerability Analysis*, **The Proceedings of the Tenth Annual Symposium on Survivability and Vulnerability of the American Defense Preparedness Association**, Naval Ocean Systems Center, San Diego, CA, 10-12 May 1988.

31. The interactive computer program which supports this function is called **ICE** (for **I**nteractive **C**riticality **E**stimator), written by G. S. Moss. Documentation appears in the **VLD/VMB UNIX Supplementary Manual**, D. A. Gwyn, Editor, Ballistic Research Laboratory, 29 August 1987.

‡ The analysis and coding for these extensions are due to Robert N. Schumacher and Aivars Ozolins, BRL/VLD.

field observables. At a minimum, the stochastic extensions under development will produce field-observable outputs.

5.2.4 Derivation of Lower-Level Models: If SQuASH is to be the key member of a V/L modeling hierarchy, then a sound strategy for referencing low-resolution models to it must be developed. The most direct way to develop low-level models that are calibrated to SQuASH is by direct derivation. One method of doing this, suggested earlier,[18] involves deriving new Compartment correlation curves from high-resolution model outputs and then using those curves as inputs to the lumped-parameter Compartment Model discussed above. In this way, the results from the low-resolution Compartment Model would be hierarchically grounded in SQuASH.

The feasibility of generating new correlation curves using SQuASH has been successfully demonstrated as shown in Fig. 4. Here the SQuASH code has been used to fire approximately 1500 shots into the side of a tank. The subset perforating into the crew compartment was used to form the left-hand plot of Fig. 4. For each M/F (read M *or* F) LoF, a corresponding Profile Hole Diameter was computed and used as the independent variable. This plot corresponds in *form* to the field-derived results shown above in Fig. 3. The M/F LoFs shown on the left were averaged by narrow bins and fitted to an exponential curve; these results are plotted on the right of Fig. 4. The aspect-averaged Compartment curve for Firepower in recent use is also shown.

If we accept this approach, we can then consider other variables that SQuASH calculates as possible independent variables with which to correlate the M/F LoF as shown in Fig. 5. Here the data derived for Fig. 4 are plotted as function of the number of critical components killed.[∞] On the right, the M/F LoF are averaged by the number of (critical) components killed and fitted to an exponential curve.

Nevertheless, the general approach of using but a single variable as a basis for describing **Space 4]** metrics is unlikely to provide a sound statistical basis for a functional representation. It is not to be expected that such complex behavior can be described by a limited set of variables. This issue will be further discussed in **Section 6**.

5.3 Validation of the SQuASH Model

In addition to verifying that the SQuASH model performs as expected, the validity of the model itself must be checked with field data. Model validation here is meant in the statistical sense of ***not*** rejecting the null hypothesis that the model predicts accurately over the input space on which the comparisons are made. For the model to be validated in a general sense, the entire space over which predictions are to be made must be sampled. For armored fighting vehicles, a matrix of heavy and light, foreign and domestic vehicles has been selected to validate the SQuASH model using live-fire data. For the validation process, only 90% of the data collected should be used. The remaining 10% should be held in reserve for model validation in the event that null hypothesis is rejected. If the null hypothesis is rejected and the conclusion is that SQuASH does not predict vehicle component-damage vectors adequately (at some statistical level of significance), then these data can be used to modify the SQuASH model and the remaining 10% of the data that were held in reserve should be used to validate the model after changes are made. It should be clear that it is not acceptable to use the same data to develop/change a model ***and*** to validate it as well. A program to develop these procedures is currently ongoing and will require a substantial expenditure of resources in order to complete over the next few years.

Once the SQuASH model has been validated over the space of vehicles, it will be the only vulnerability model validated with full-scale, live-fire tests and indisputably the key member model for application to armored fighting vehicles. Other vulnerability models do not produce metrics that are

∞ The abscissa values of the points have been dithered to make the full set of points more visible.

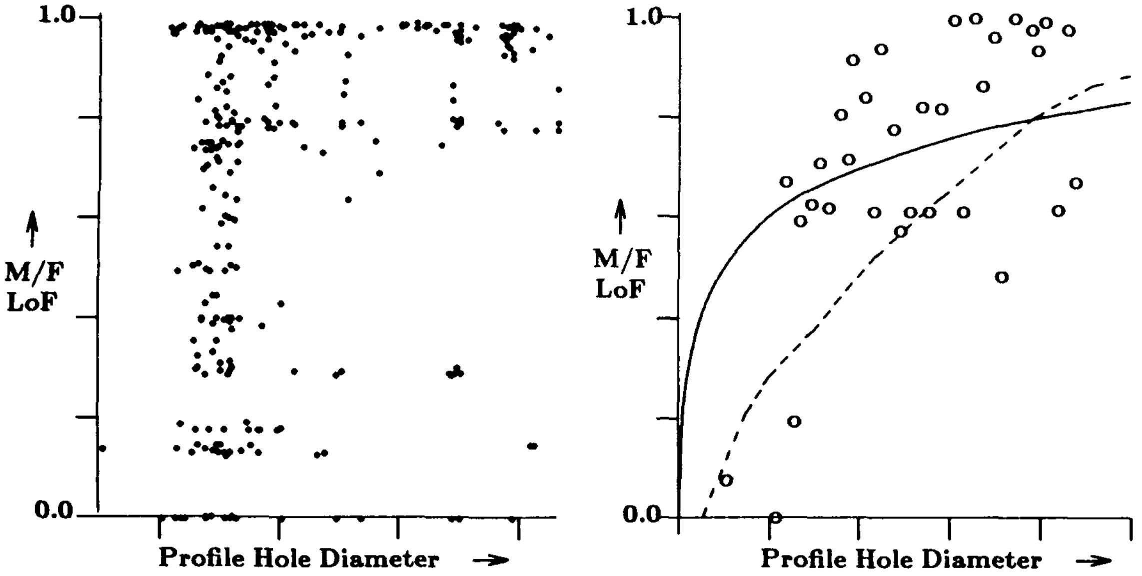

Figure 4. Predicted M/F LoFs vs. Profile (≃ Exit) Hole Diameter. On left, all shots which impacted crew compartment. On right, (o)- M/F values averaged by narrow bins; (—)- exponential curve fit to averaged values given by (o); (– – – –)- aspect-independent damage correlation curve for Firepower.

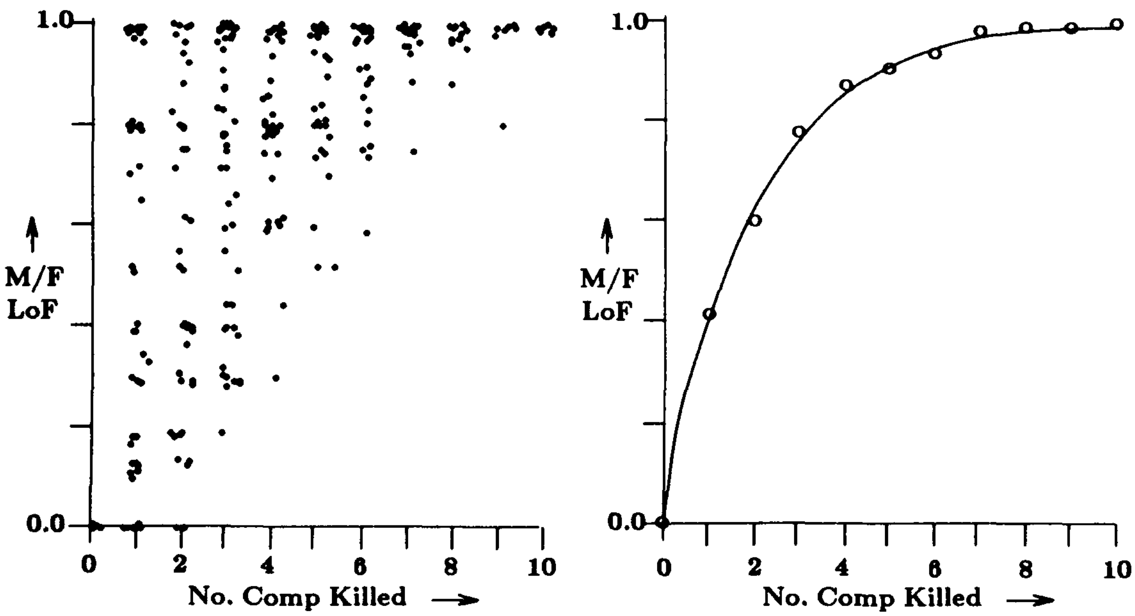

Figure 5. Predicted M/F LoFs vs. Number of Critical Components Killed. On left, raw data for those shots which impacted crew compartment. On right, (o) give expected M/F LoFs vs. number of critical components killed; solid line (—) gives exponential curve fit.

appropriate for comparison with individual samples produced by live-fire test programs. Furthermore, SQuASH is being validated at every level at which data can be collected or measured in live-fire testing.

6. FUTURE DIRECTIONS IN V/L MODELING

The development of the high-resolution stochastic point-burst model and the validation of that model raise possibilities for the development of a low-resolution model. One of the requirements that makes a low-resolution model necessary is the need to conduct vulnerability analyses of concept vehicles. For such applications, detailed inputs are not available (by definition) for performing a SQuASH-level of high-resolution analysis. A desirable property of such a model is that it be subject to rapid configuration and execution.

An alternative is to find a way of making quick turn-around V/L estimates which is simultaneously calibrated with high resolution modeling but avoids the difficulties that we have seen are associated with deriving new Compartment correlation curves. One possibility involves abandoning the notion of "calibration" altogether and simply using the high-resolution model for all required V/L estimates. There are several objections to this. One objection concerns the high level of resources required for SQuASH modeling, in particular, the long lead time required for conduct of this kind of analysis. We believe that while this objection can be overcome in principle, it cannot currently be overcome in practice. Although many computer aided tools have been developed to assist with geometry editing[9] and fault-tree construction,[31] there is still considerable overhead in reconfiguring the input files for any high-resolution (*e.g.* point-burst) V/L simulation.[□] A second objection to the strategy of using high-resolution modeling for some V/L purposes is that we do not often have sufficient detailed information available concerning component sizes, locations and $P_{K/H}$'s. This is obviously true for many foreign vehicles to which the US does not have access. However, it is not clear that the objection is a strong one. If sufficiently detailed information is not available about all vehicle components, then a reasonable assumption is probably that the future will be like the past. If a previous generation tank had a radio of a certain size and location, then assume (in the absence of information to the contrary) that future tanks will also have that radio in the same location. We note that some version of this assumption is made -- implicitly when a Compartment correlation curve for a "specified" vehicle is applied against a "loosely specified" vehicle.

The current Compartment Model qualifies as a low-resolution model. However, it is not currently referenced to a high-resolution model nor is it a particularly responsive analytical tool. Of these two shortcomings, the former can probably be rectified but not necessarily the latter. The more important issue is the statistical validity of the general approach. Thus a new low-level vulnerability model is being sought.

One promising solution to this problem involves the generation of a regression equation derived from SQuASH to form the low-resolution model. Since SQuASH is configured to retain initial, intermediate and final computations together with all supporting data files, it provides a wealth of variables for use in regression analyses that would presumably contribute to various vehicle **Space 4**} metrics. One of the difficulties of this approach will be to assure that the assumptions for regression analyses are met and that no statistically pathological problems (*e.g.* collinearity, outliers) effect our model. Another problem with this approach is that the parameters that determine the **Space 4**} metrics for the high-resolution model must be rolled-up to the level of parameters available for concept vehicles while ***retaining sufficient accuracy to be useful***.

□ The Abrams M1A2 target description consists of 5000 objects, 750 of which represent critical components. Each of these components appears at least once among some 76 fault trees. Reconfiguring the target can involve the modification (resizing, reorientation, deletion) of any of the 5000 objects or the addition of new entities. If any change involves critical components, the related fault trees and component $P_{K/H}$'s must be reworked as well.

Another low-level modeling approach that could be considered is an engineering or analytical model that incorporates the effects of the target rather than the current approach in which geometry is explicitly built and raytraced. It has been shown in the first phase of the sensitivity analysis that is currently being conducted on the Compartment Model that this approach is feasible for at least some Compartment Model vulnerability measures and for certain classes of threats.[32] Again this approach has potential pitfalls. If an analytical model were developed using information available at the initial concept stage (*i.e.* information available in the current Compartment Model), it must still be calibrated using SQuASH. Neither of these approaches is sufficiently developed to speculate on the probability of success. In each instance only preliminary computations have been made to demonstrate the approach as having possible merit.

We have asserted above that a set of regression equations with associated statistical uncertainties will be used in the future to make rapid-response V/L estimates. A final remark is appropriate to elucidate the likely extent to which such regressions will prove statistically useful in evaluating modified or new targets. The multidimensional response surface implicit in our regression will be statistically valid for a new application only if the values of the regression variables characterizing the weapon and target are within the envelope of SQuASH initial conditions that were used to develop the regression equations in the first place. Since many of the engineering changes made to weapon systems are of the incremental or product-improvement type, it is reasonable to suppose that the regression strategy will be adequate for most analytical purposes. However, we must explicitly caution that, for radically new concepts or technologies, there can be no V/L simulation method that is simultaneously quick turnaround and statistically defensible. For break-throughs, which are outside the envelope of our regression space, we see no defensible simulation alternative that does not require resort to high-resolution analysis.

7. VLD MASTER PLAN

Based on the evidence summarized above, we assert the following:

- **PRINCIPLE I:** The assessment of ***accuracy*** and ***precision*** in V/L modeling is founded upon the application of appropriate statistical assessment tools to predictions of target damage vectors. Such vectors are the observable of LF testing; they are also the unique yield of the stochastic V/L model SQuASH. Therefore **Space 2**} comparisons between (field) observed and (computer) predicted damage vectors can reveal the limitations of extant predictive tools and their ability to characterize accurately the effect of all relevant damage mechanisms.

- **PRINCIPLE II:** If reliable damage vectors can be estimated, new Measures-of-Effectiveness can be formulated in order to meet the evolving needs of relating vulnerability damage to application-specific utility. Therefore new and useful extensions to **Space 4**} can be implemented to extend the utility of the key damage vectors of **Space 2**}.

- **PRINCIPLE III:** Where needs arise for models of lower resolution than the reference model, those models should be derived directly from the high-resolution (stochastic) estimates. Bounding confidence intervals, intrinsic elements of the reference model, will carry over to lumped-parameter derivations. Very likely the current Compartment Model approach, in which damage correlation curves (*e.g.* Fig. 4) are based on a single parameter (*e.g.* profile hole diameter), will give way to models based on full exercise of multiple inputs and examined through modern statistical methods such as the Analysis of Variances.[33]

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32. William E. Baker, Joseph C. Collins, Elizabeth A. Laurie, Jill H. Smith and Wendy A. Winner, ***Sensitivity Analysis of the Compartment Model to Cell Size and Symmetry for the Abrams Vehicle***, **Ballistic Research Laboratory Memorandum Report**, In Preparation.

33. Charles R. Hicks, **Fundamental Concepts in the Design of Experiments**, Third Edition, Saunders College Publishing, Fort Worth, TX, 1982.

- **PRINCIPLE IV:** The **PRINCIPLES I-III** are *generic* in nature. That is they apply without regard to the *specific class* of threat/target interactions. As such, all targets, aircraft, communication shelters, as well as mobile ground systems are amenable to this strategy of analysis.

Therefore based on these **PRINCIPLES** and the arguments upon which they are based, we propose the following plan of action. Choose a set of targets that at least minimally covers those systems that are important to the Army mission, are fundamentally different one from another, and will have been subjected to live-fire testing. Proceed with each using the following steps:

1. Fully configure SQuASH for a given target. This includes full development of high-resolution geometry, component $P_{K/H}$'s, and the inclusion of all phenomenologies likely to play a role in producing target damage for the threats under evaluation.
2. Perform live-fire tests on the target.
3. Perform SQuASH calculations for each LF shot.
4. Use 90% of the data collected to validate the model using various statistical methodologies. If the null hypothesis that the model predicts vehicle LoF accurately is not rejected, then proceed to Step 8.
5. Upgrade the model to account for discrepancies observed between the live-fire data and the model using the same data (90% portion).
6. Validate the model using the 10% of the data held in reserve; if not rejected, proceed to Step 8. If the hypothesis is again rejected, go to Step 5 to examine whether further upgrades can be made.
7. Collect additional data to validate the model.
8. Derive lumped-parameter model relations through suitable statistical analyses (*e.g.* regression) in order to relate **Space 1**] initial conditions to **Space 4**] metrics.

Thus far, VLD has partially completed an analysis of this type for only one target. Consistent with the four **PRINCIPLES** articulated above, VLD has near-term plans for high-resolution stochastic analysis of several additional targets and classes of targets. Highest priority targets for this work are domestic and foreign tanks, infantry fighting vehicles, self-propelled howitzers and helicopters. The first to be examined will be two heavy tanks and at least one system from each of the other classes. For most of the targets analyzed, this will permit us to make **Space 2**] comparisons between computed damage vectors and empirically derived vectors from actual shots. These comparisons will also permit us to evaluate the evolving statistical tools for evaluating the accuracy of our predictions. This analysis will also require us to develop **Space 4**] Degraded State (DS) kill definitions for the new targets and classes of targets. Use of the DS kill definitions for calculation of **Space 4**] MoEs will provide further proof of the robustness and utility of the DS methodology. Moreover, the set of SQuASH **Space 2**] outputs and derivative **Space 4**] DS metrics will provide, for the first time, an adequate set of raw data to execute the lower-level model calibration described above in **Section 5.2.4**. At this point we will have sufficient information in hand to address questions coherently concerning economical variable sets for analysis and whether one or many sets of regression variables are required.

Last, and probably most important, the critical path to these objectives *requires* the successful prediction of critical-component damage vectors (of **Space 2**]) for all threat/target pairings. To be successful in this endeavor, all significant damage phenomenologies (*e.g.* spall, blast, shock) will have to be confronted, supporting data bases generated and LF test results thoroughly examined in order to establish a credible predictive capability. If even partial success towards this goal is achieved over the next few years, the sunk investment in LF testing will be enhanced many fold.

8. SUMMARY AND CONCLUSIONS

In this paper we've reviewed a series of developments and plans in the area of Vulnerability/Lethality simulation. To summarize:

- There are many important and diverse applications of V/L data, each with specific requirements for form, accuracy, cost and timeliness.
- Over the past fifteen years a body of criticism of V/L assessment practice has developed, some of which is technically justified.
- An analytical framework has been established within which the many vulnerability states and transformations can be understood with respect to both field testing and high-resolution simulations. Further, a high-resolution stochastic tool, SQuASH, has been developed that replicates in simulation the same sequence of processes that occur in actual live-fire tests.
- The V/L modeling paradigm described here can be generalized to *all* classes of military targets by tailoring the damage algorithms to the relevant threat phenomena.
- We suggest that a critical set of military targets, a group of those already undergoing live-fire testing, be subjected to stochastic analysis. By comparing the field observable damage with model predictions ***within the context of our newly emerging statistical perspectives***, confidence bounds can be established not only for those field-observable metrics, but all other related V/L measures.
- If appropriate levels-of-confidence can be established for predictive component-damage vectors ***via*** the reference models ***by target class***, then all other V/L metrics can be supported. These include extended Measures-of-Effectiveness, spare-parts calculations and lumped-parameter regression modeling.

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